



Planetary Drilling and Resources at the Moon and Mars

Pioneer Natural Resources

Geoscience, Engineering and Drilling Technology Conference

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Jeffrey A. George

NASA Johnson Space Center

EP / Propulsion and Power Division

Houston, TX 77058



Abstract



Planetary Drilling and Resources at the Moon and Mars

Drilling on the Moon and Mars is an important capability for both scientific and resource exploration. The unique requirements of spaceflight and planetary environments drive drills to different design approaches than established terrestrial technologies. A partnership between NASA and Baker Hughes Inc. developed a novel approach for a dry rotary coring wireline drill capable of acquiring continuous core samples at multi-meter depths for low power and mass. The 8.5 kg Bottom Hole Assembly operated at 100 We and without need for traditional drilling mud or pipe. The technology was field tested in the Canadian Arctic in sandstone, ice and frozen gumbo.

Planetary resources could play an important role in future space exploration. Lunar regolith contains oxygen and metals, and water ice has recently been confirmed in a shadowed crater at the Moon's south pole. Mars possesses a CO₂ atmosphere, frozen water ice at the poles, and indications of subsurface aquifers. Such resources could provide water, oxygen and propellants that could greatly simplify the cost and complexity of exploration and survival.



Bio



Jeffrey A. George

NASA Johnson Space Center

EP3 / Propulsion and Power Division

Houston, TX 77058-3696

jeffrey.a.george@nasa.gov

281-483-5962

Jeff George is a project manager, systems engineer, technologist, and advanced mission planner at the NASA Johnson Space Center in Houston, TX. His responsibilities include developing mission architectures for human exploration of the Moon and Mars; leading the NASA/JSC Nuclear Systems Team to plan, assess and develop space nuclear power and propulsion technologies; and serving as Mission Architect for the planned RESOLVE lunar resource mission. Jeff led the successful collaboration of NASA and Baker Hughes Inc. to develop a low mass and power drilling technology through two prototype cycles and field testing in the Canadian High Arctic. Jeff earned his B.S. and M.S. in Nuclear Engineering from Texas A&M University.



Contents

30-45 min

40 charts



- ***Introduction***
 - 4 charts

- ***Planetary Drilling***
 - 26 charts
 - Why Drill? – 2
 - Apollo Drilling Experience – 7
 - NASA/Baker Hughes Mars Drill Prototype – 5
 - Arctic Field Testing – 9
 - Rover Drilling & Accomplishments – 3

- ***In-Situ Resources at the Moon and Mars***
 - 9 charts
 - Type, Use and Value – 3
 - Production and Conversion – 4
 - Prospecting and Missions, RESOLVE – 2

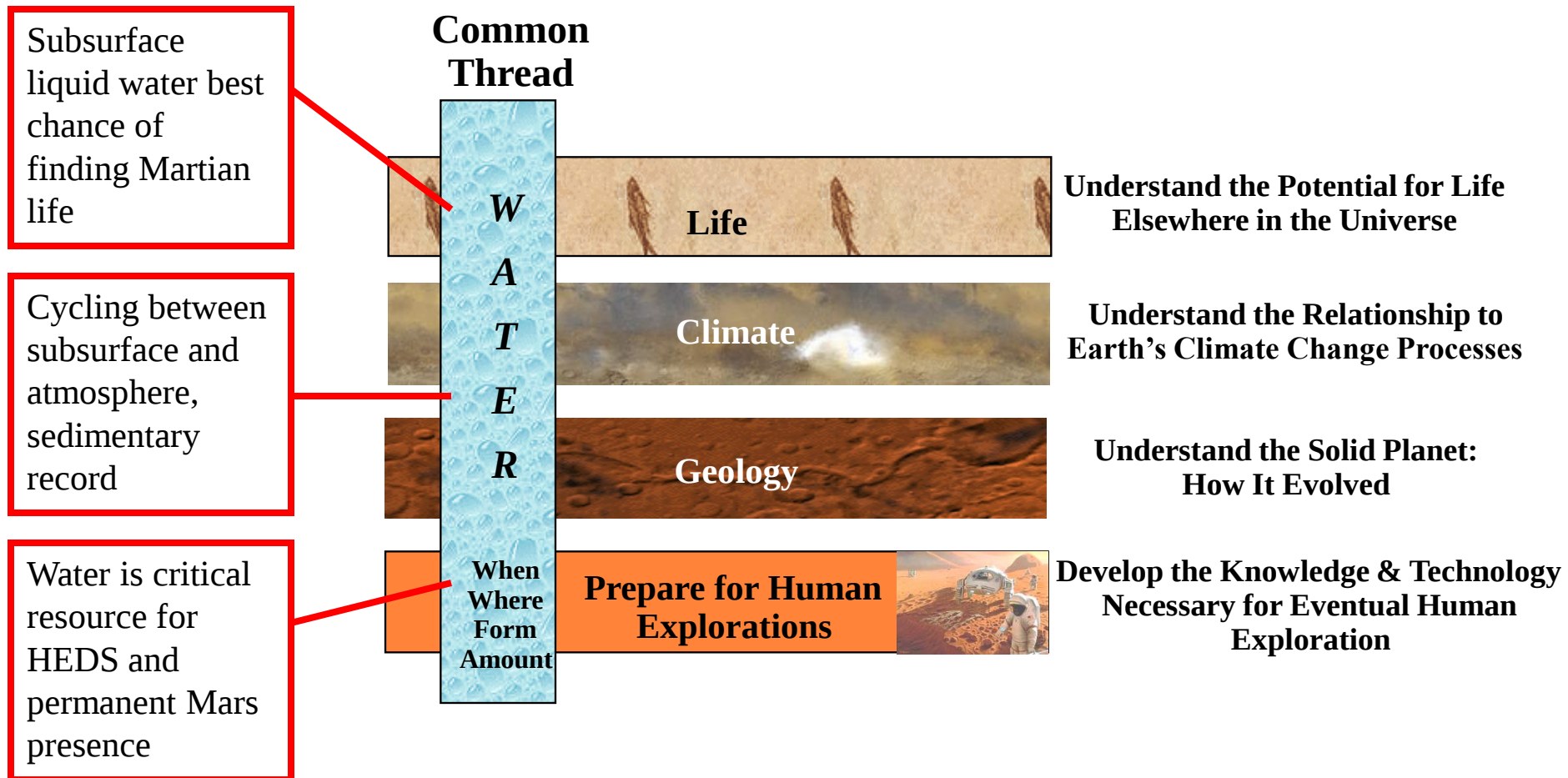
- ***Summary***
 - 1 chart

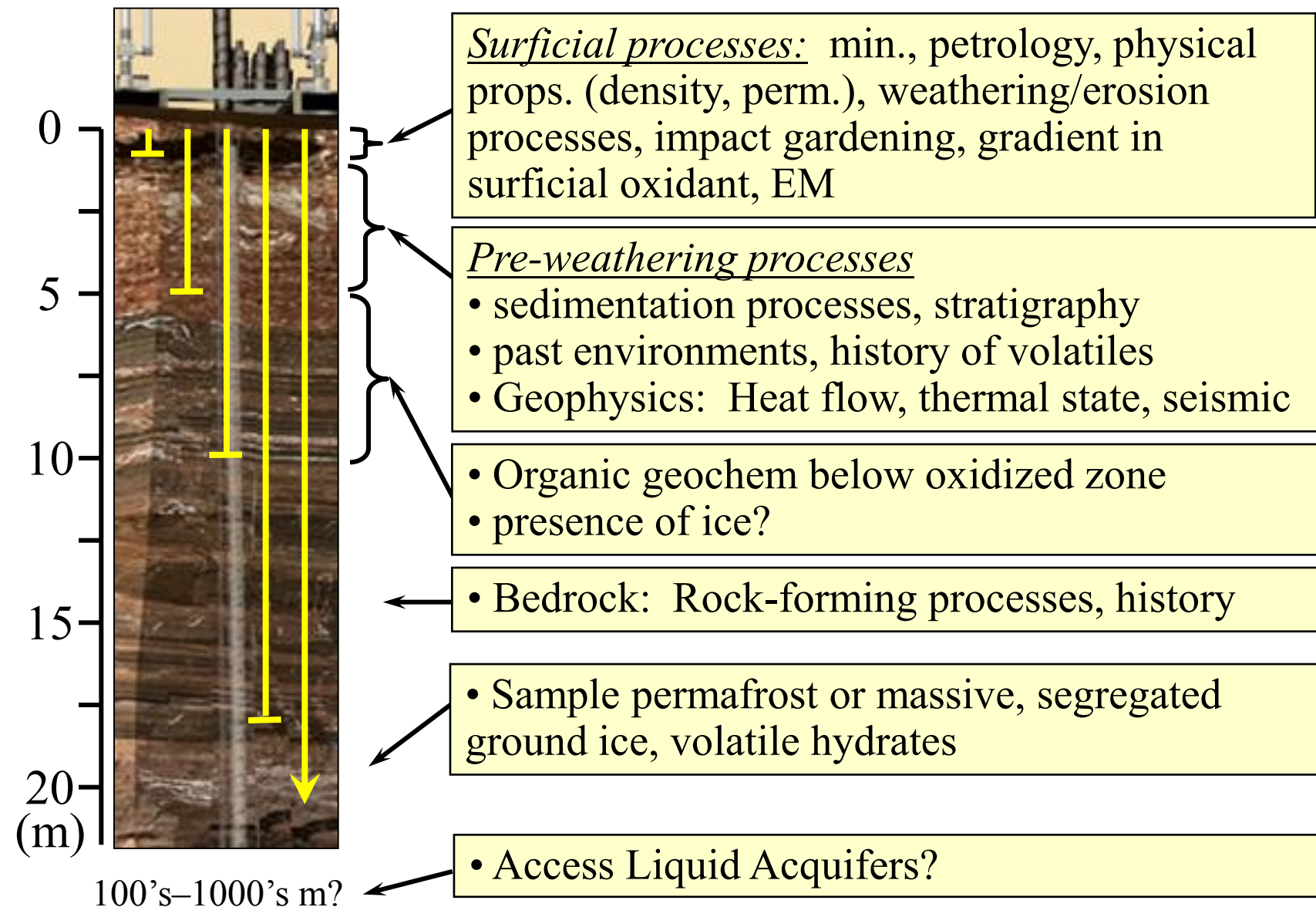


Why Drill ?



Mars “Follow the Water” Strategy







Apollo Lunar Surface Drill (ALSD)

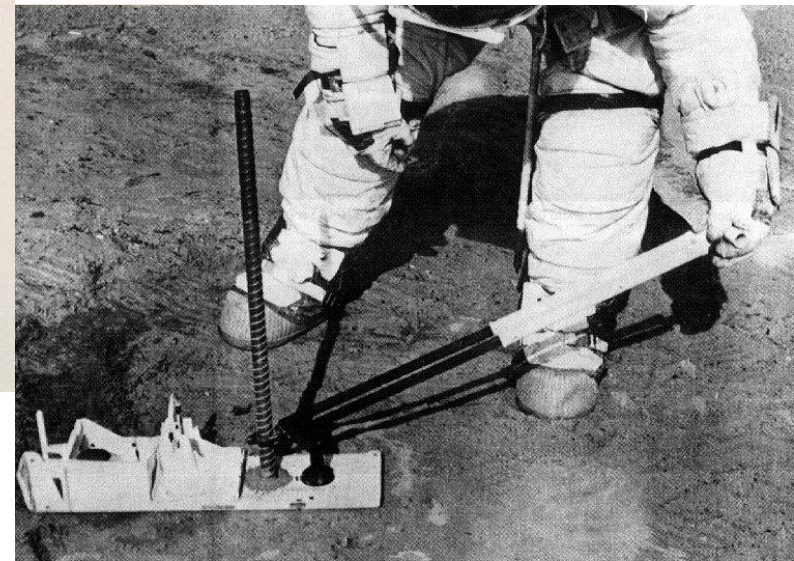
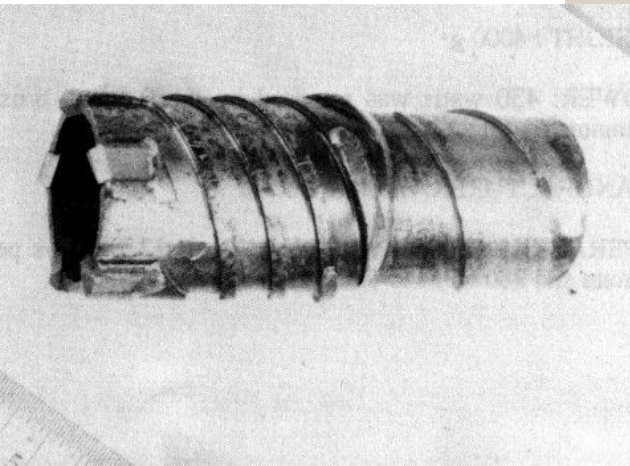
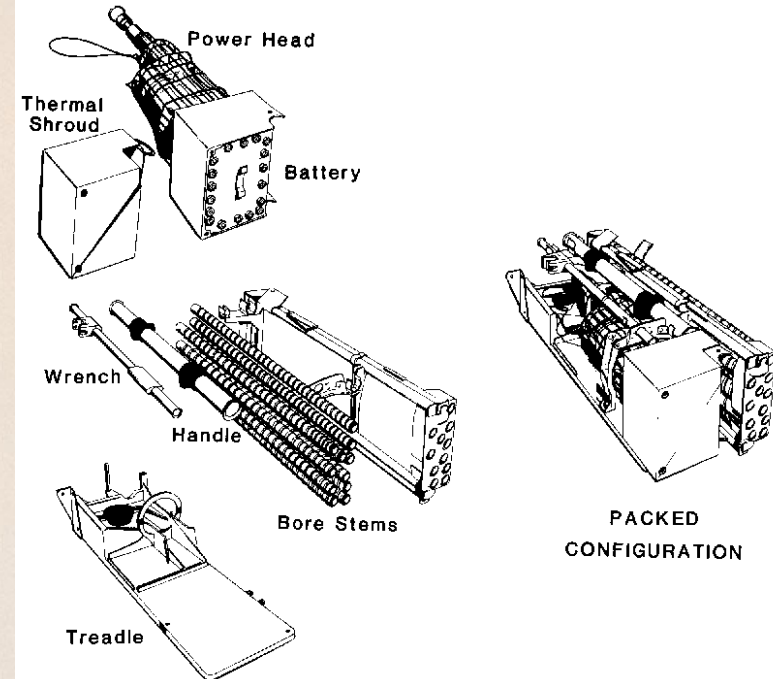
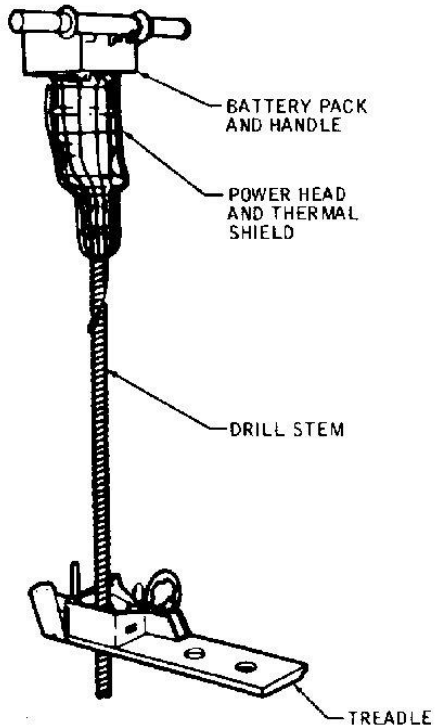


- **First “Cordless” Drill (?)**
- **Martin-Marietta, Black&Decker**
- **Handheld drive unit**
 - Battery powered
 - ~430 - 500 W
- **Rotary-percussion action**
 - 280 rpm
 - 2270 bpm
 - 40 in-lb / blow
- **Coring Bit:**
 - 6 cm long x 2 cm ID
 - Steel body + 5 brazed tungsten carbide tips
- **Drill stem:**
 - 40cm long, 2.5cm OD, 2.0cm ID
 - Titanium alloy
 - External auger flights
- **Carrier & Treadle/removal tool**
- **Total depth capability = 3.0 m**
- **Total system mass = 13.4 kg**





ALSD Elements



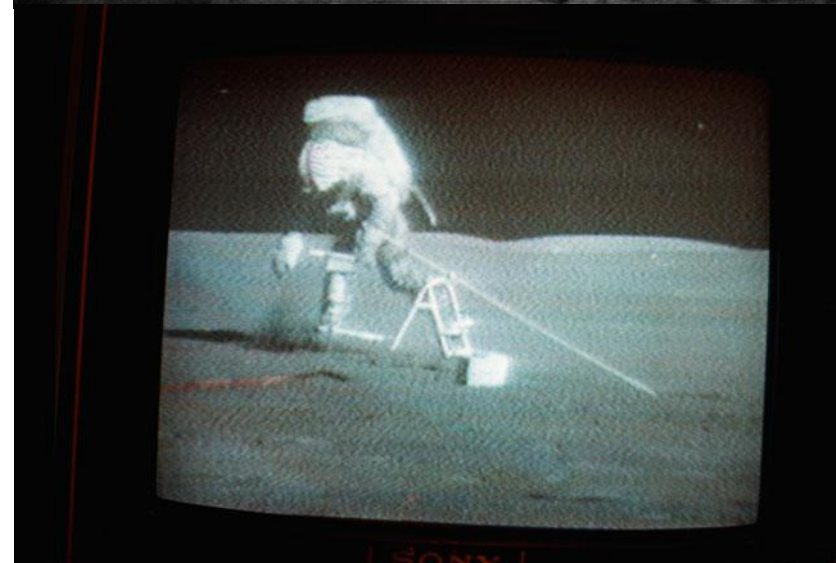
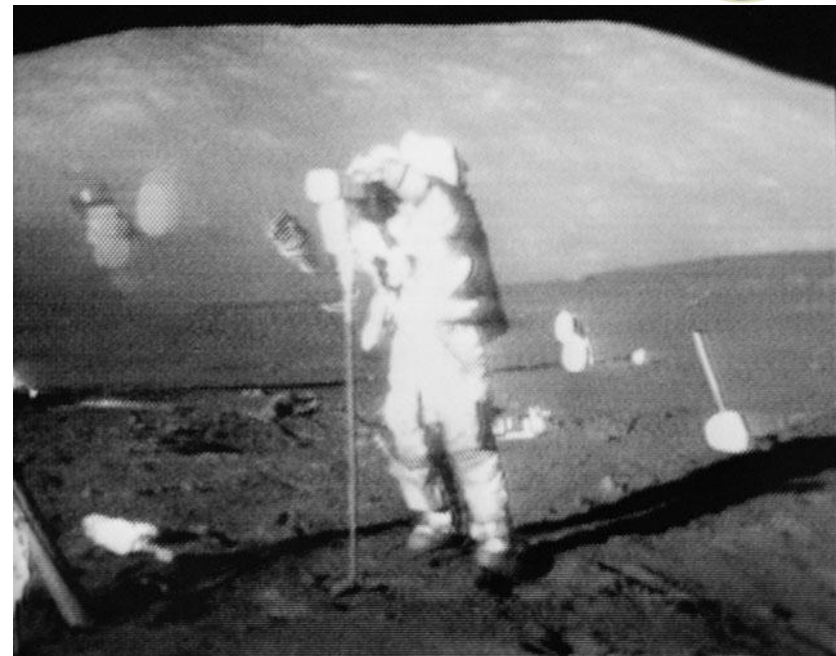


Apollo Lunar Drilling Results



- Flew on Apollo 15, 16, 17
- Purpose:
 - Acquire core samples
 - Emplace heat flow thermocouples
 - Neutron probe
- ~5-15 minutes to drill each hole
- Astronauts learned to:
 - “Hold-back” as drill advanced
 - Clear cuttings to surface before remove
- A-15 drill stem very difficult to remove
 - Both astronauts & sprained shoulder
- Redesign & “treadle/jack” aided 16, 17
- 7.6 m cum. Exc. recovery & stratigraphy
- Regolith: jagged, interlocked agglutinates
- Top few cm’s: “fluffy” unconsolidated
- Deeper cm’s: closely packed, 1.6-2.1 g/cc.
- Hope: Cores would reflect slow evolution history of surface
- Cores surprisingly homogenous- no distinct ancient surfaces found
- Deepest core last exposed ~1B yr ago

NASA/JSC/EP/JAG



Other Apollo Sampling Tools

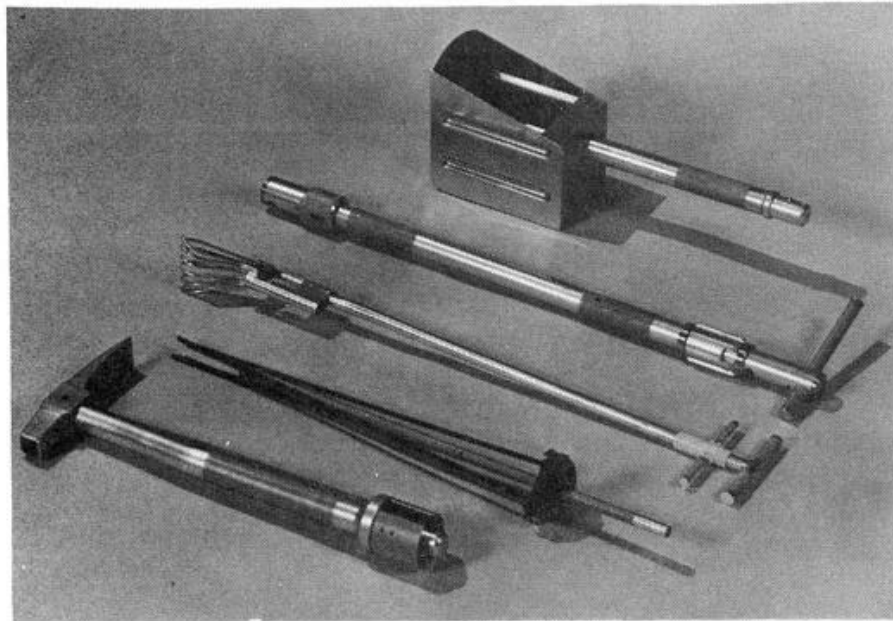
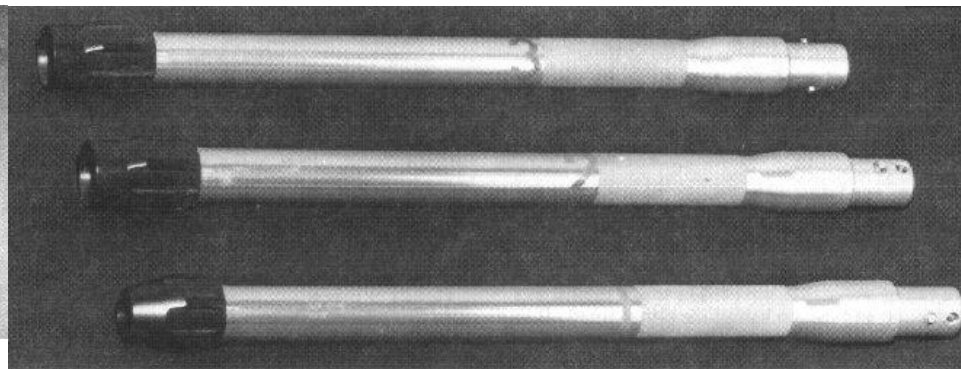


Fig. 26. Tools of the type used on Apollo 11 (L to R): lighter weight hammer, gnomon, shorter tongs, shorter extension handle, box-shaped scoop. The extension handle was used with the hammer and the scoop (NASA photo S69-31860).

NASA/JSC/EP/JAG

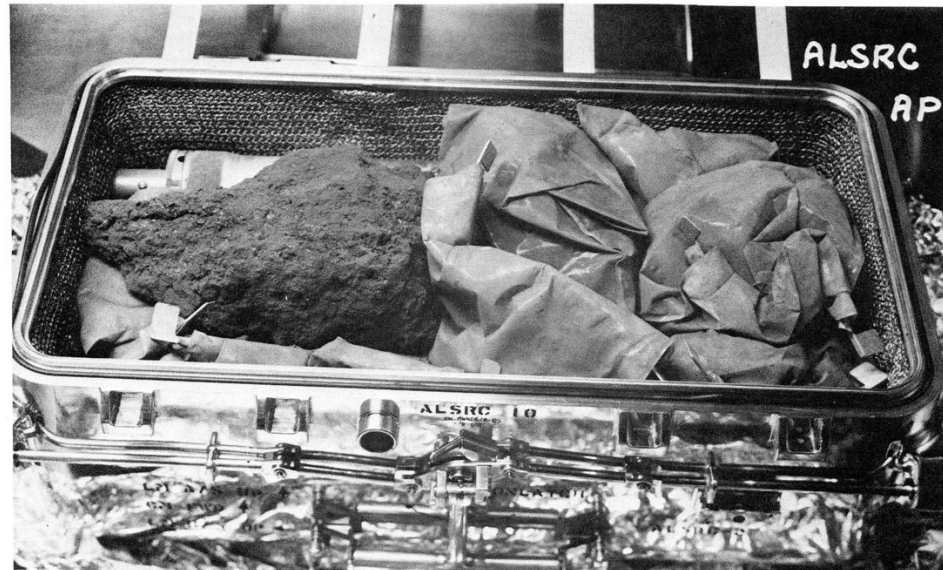


Fig. 72. Apollo 16 Lunar Sample Return Container upon opening in the Lunar Receiving Laboratory. The box contains a large rock, several documented sample bags with the fold-over aluminum tabs, and a 4-cm diameter drive tube (NASA photo S72-36984).

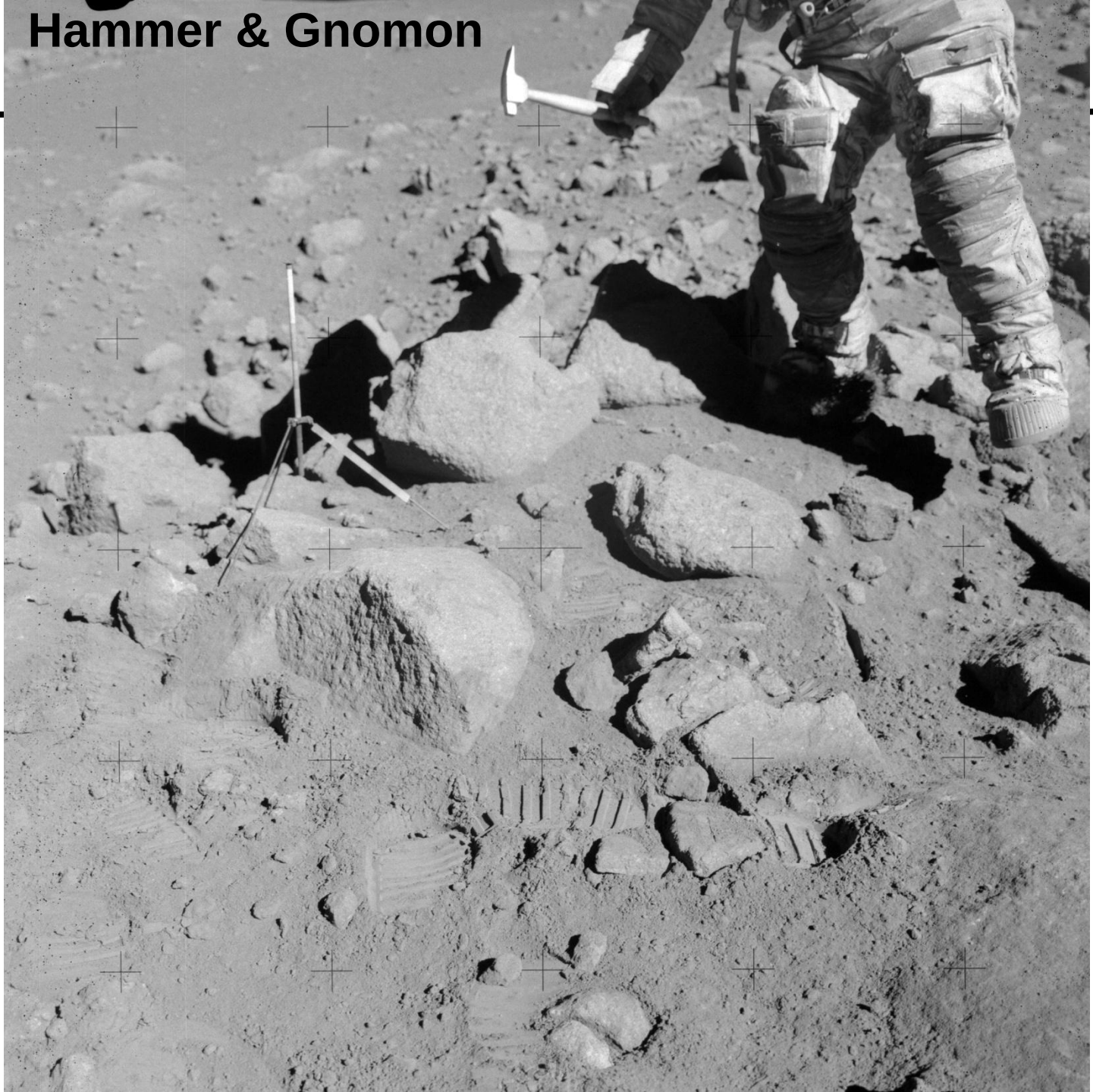


Tongs & Rake





Hammer & Gnomon





Rake

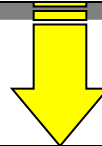




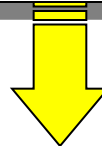
Drill Project Goals & Objectives



Vision (why): Explore Mars' subsurface, to understand history, climate, life, and resources.

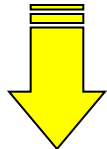


Mission Statement (what): Develop a deep drilling and sample acquisition capability.



Project Major Goals:

Goal I:
Advance Drill to TRL=4
(System in lab environment)

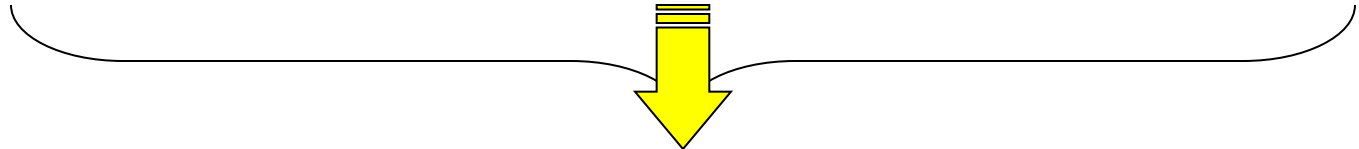


**"Mark I" Mars Drill Project
Objectives & Requirements**

Goal II:
Advance Drill to TRL=5
(System in field environment)

Goal III:
Participate in M/ADD Project
and demonstrate in Arctic

Goal IV:
Demonstrate Rover-deployed
drilling



**"Mark II" Mars Drill Project
Objectives & Requirements**



NASA / Baker Hughes Inc. Mars Drill

Space Act Collaboration



- **NASA / Johnson Space Center / EX**

- Project Management
- System Design, Integration, and Test
- BHA Assy (Anchor, Force-on-Bit, Drive Motor)
- Surface Support Assembly
- Control Electronics (Hardware)

- **Baker Hughes Incorporated**

- Industry Partner
- Drilling Mechanics
- Ops. Expertise
- BHA Auger, Bit, Core Break/Trap S/A's

- NASA/JSC / SCOUT Rover
 - Mobility; Rover/Drill Demo

- NASA/JSC / EC Rover
 - Mobility; Rover/Drill Demo

- NASA/JSC/ EX ACES Van
 - Remote Operations Demo

- NASA/JSC / ARES
 - Moon Science Objectives
 - Moon Subsurface Environment

- NASA / Ames Research Center
 - PI for Code S/ASTID “M/ADD” Project
 - Automation

- Lunar and Planetary Institute
 - Mars Science Objectives
 - Mars Subsurface Environment

- UC Berkeley
 - Fundamental Research
 - Component Laboratory Testing
 - Modeling and Simulation

- University of Texas
 - Leadership & Outreach

- MacGill University; University of Toronto
 - Arctic Multidisciplinary Science
 - Sample Contamination



Challenges of Drilling on Mars:

- Achieving Depth
- Limited Mass
- Limited Power
- Aseptic Sampling
- No Drilling Fluids:
 - Cuttings Removal
 - Heat Transport
 - Sample Contamination

Our Approach:



Drilling Function

- Sample acquisition
- Comminution
- Cuttings Removal
- Torque
- Force-on-bit
- Power Transmission
- Cooling

Technical Approach

- Dry
- Rotary Coring Bit
- Downhole Motor
- Wireline
- Bailing
- Borewall Anchoring
- Internally applied Force-on-bit

Features

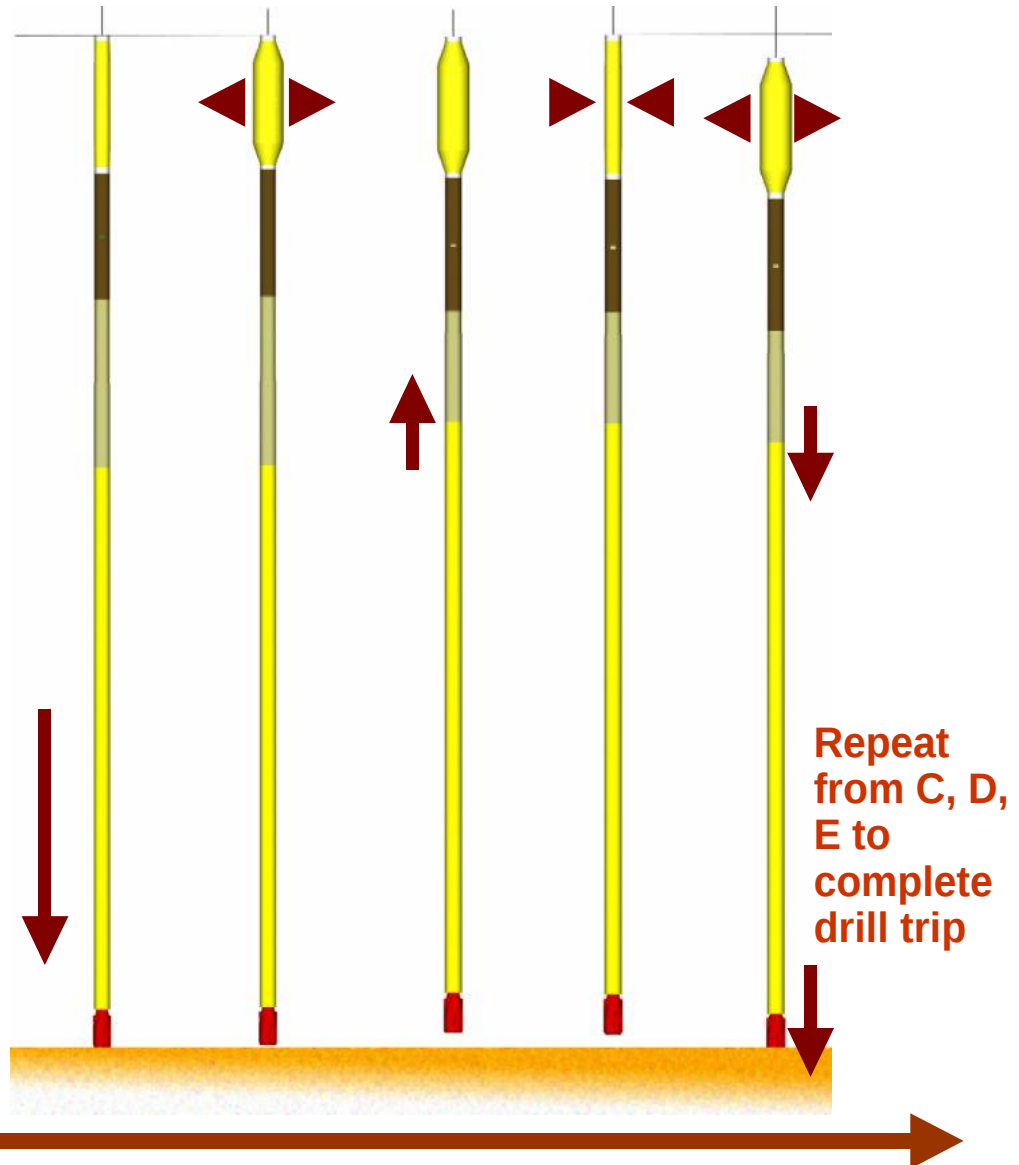
- Continuous Core & Cuttings Record
- Low Sample Contamination
- Low Mass
- Low Power
- Deep capable
- Modest Penetration Rates
- Sensitive to Formation Stability



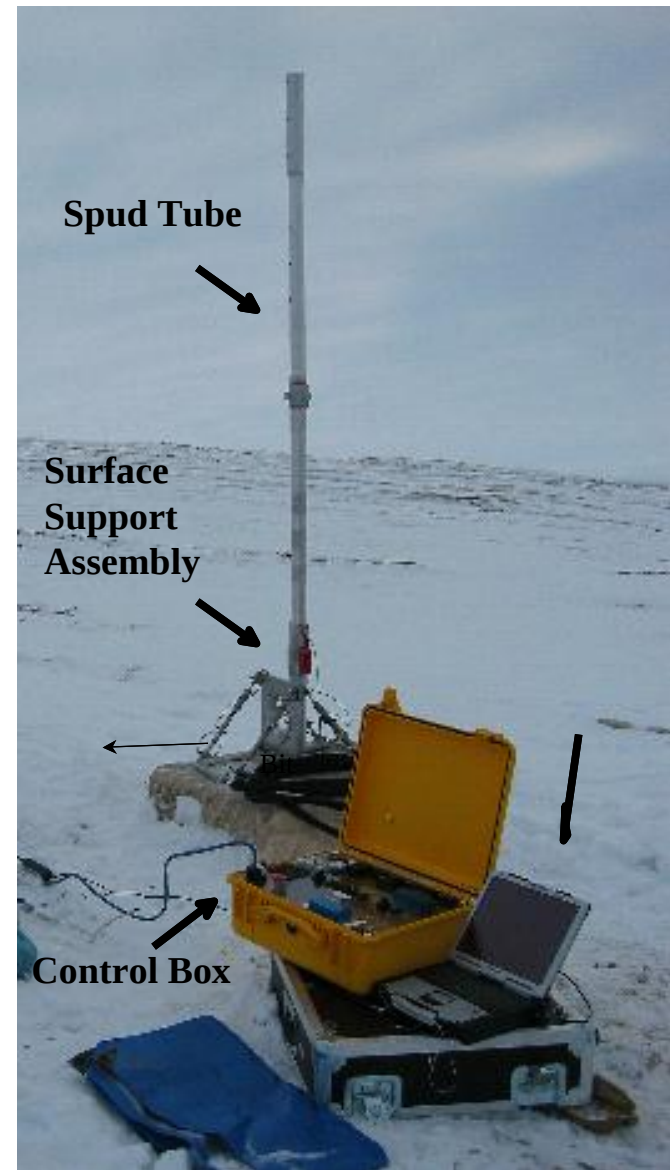
Coring / Bailing Operational Sequence



- A – Initial Deployment, Tool is Lowered to tag the Bottom of the Drill Hole**
- B - Anchor Module is Expanded against bore**
- C – The winch pulls up on the wireline, setting and latching the FOB spring**
- D – Anchor is Contracted; Tool is lowered to tag the Bottom of the drill hole to initiate drill bite.**
- E – The Anchor is expanded, drill motor is started and the FOB Spring is released so that drilling force is placed on the rotating drill bit.**



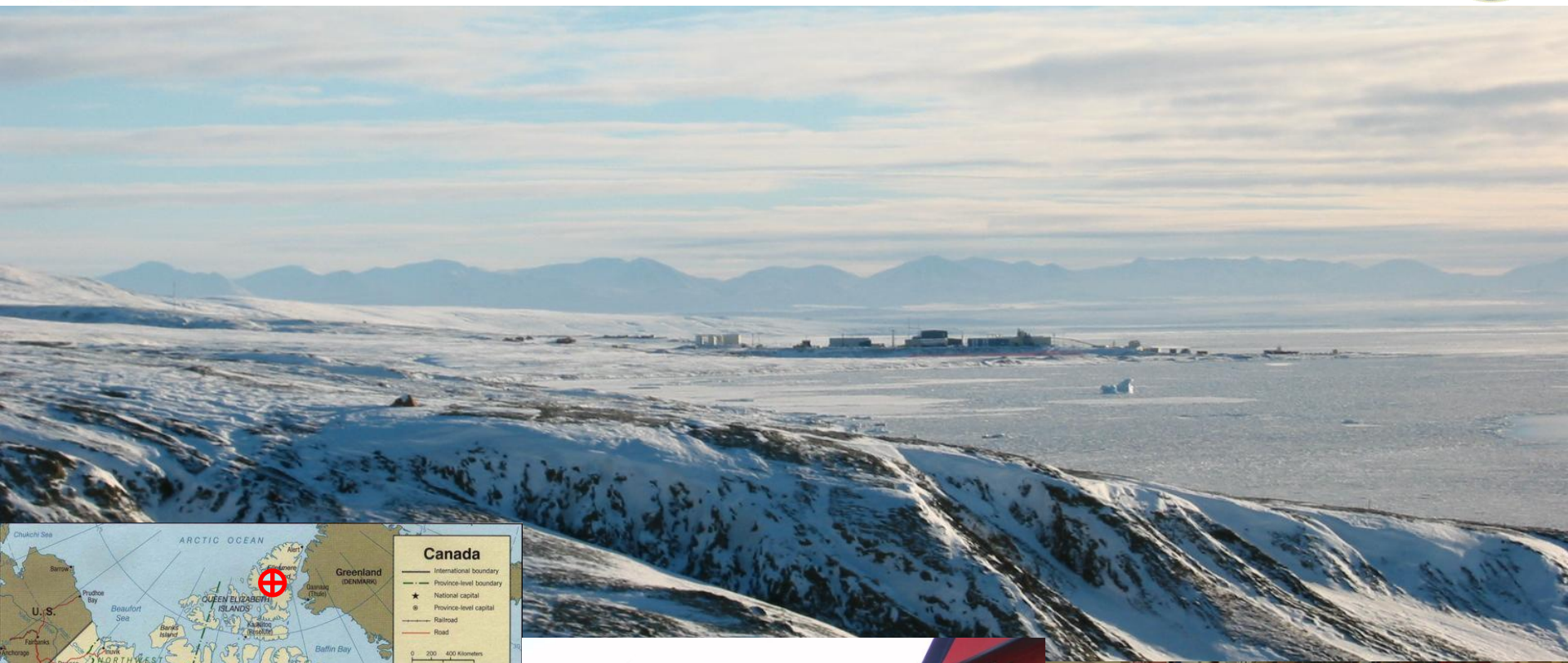
- **Bottom Hole Assy (BHA):**
 - **General**
 - Length: Approx. 7 feet
 - Diameter: approx. 1.75 inches
 - Weight: ~30 lbs
 - **Electrical**
 - Continuous Power: 100 W
 - Peak Power: 200W
 - Max. Voltage sent to BHA: ~30VDC
 - **Mechanical**
 - Max. Force-on-Bit: -200 to +200
 - Internal Stroke of AFOB Spring: ~0.25 inch
 - Drill Bit/Auger RPM: 0-225
- **Umbilical / Tether** (Power, Data, Recovery)
- **BHA Control Box (yellow box)**
 - Input Power: 120 VAC @ (.8 amps nominal)
 - Weight: 35 lbs
- **Surface Equipment (weight)**
 - Rock Support Fixture: ~25 lbs
 - Spud Tube: ~10 lbs
- **Laptop: Panasonic Toughbook**
- **Software: Labview** (Logging & Control)





Eureka Weather Station

Ellesmere Island, Canadian High Arctic





2006 Field Testing



Eureka, Ellesmere Island, Canada.





Field Test - Specific Ops

Ellesmere Island, Canadian High Arctic



2006 Site Locations

Drop-Off Point at Road

(~300 feet below in elevation)

Site 1: Sandstone

Site 2: Ice Wedge





2006 2m Sandstone





2004 Ice Drilling – 2 meters





Critters





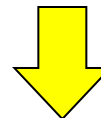
2004 Chris-Rock Cores & Bites



- Second Sandstone Bore, Eureka, Sept. 2004

- Bore Depth = 21.2" (0.5 m)
- Total Core lengths = 21" (0.5 m)

New Bit, Reaming



Sunday

Tuesday

<u>Bite #:</u>	1	2	3	4	5	6	7	8	9
Length:	2.8"	4.0"	5.0"	3.8"	1.5	1.0	1.0	0.5	2.0"
ROP:	3.4"/hr	5.5	5.6	4.2	2.5	1.9	2.0	1.4	2.7"



<u>Core #:</u>	1	2	3	4	5	6	7	8
Length:	2.6"	3.5"	5.4"	3.1"	1.4	1.2	1.1	2.3"



Field Performance: 2004 vs 2006



PERFORMANCE:	2004	2006
Max. Depth in Sandstone	0.5 meter	2 meters
Cum. Depth in Sandstone	1.1 meters	2 meters
Depth in Ice	2 meters in iceberg (1)	1 meter in ice wedge (2)
Average Drilling Rate	3.6 in/hr	8.1 in/hr
Average Drilling Power	60-120 Watts electric	60-175 Watts electric
Time on Bottom	724 min.	573 min.
Total Number of SS cores	16 cores	24 cores
Total Number of Drill days	5	5

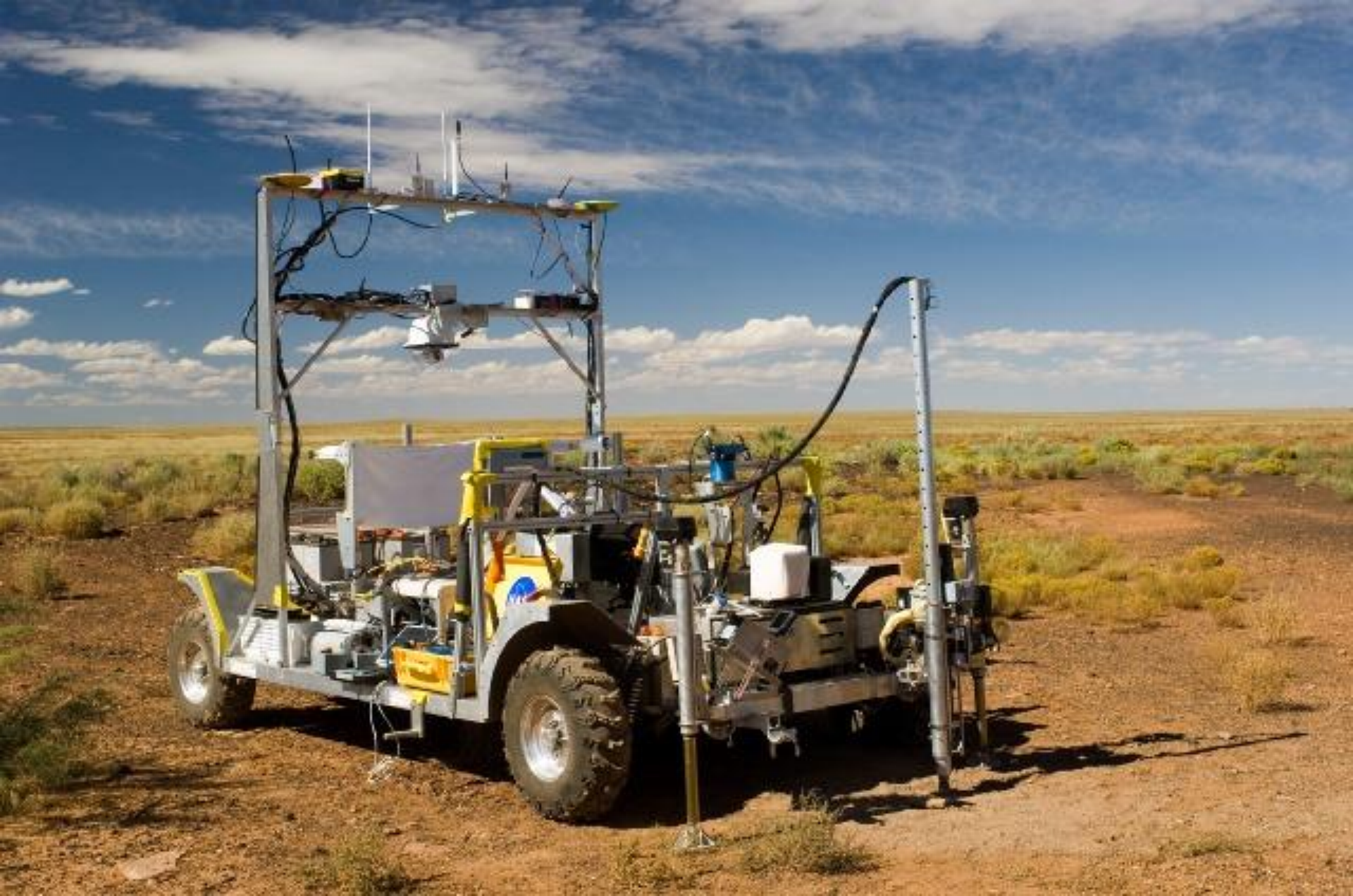
(1) With MK IIa drill motor (manual force-on-bit))

(2) With MK IIb auger/drill bit (manual force-on-bit)



JSC / Baker Hughes Drill

Field Ops w/ Scout Rover, Meteor Crater AZ, Sept. 2005





Rover/Drill System Key Elements



- Scout Rover
- Mk2b Drill (BHA)
 - Spud Tube
 - Linear Actuator
 - Pitch, Roll Actuators
 - Inclinometer
 - Stabilization Jacks
 - Custom Bumper
- Infrared Camera
- Visual Camera
- Also (not shown):
 - Drill Control
 - RSA Control
 - Laptop & Labview S/W
 - Operators



JSC/BHI Mars Drill Accomplishments



- **Successfully Achieved Major Project Goals:**
 - Mk1 Prototype Development, Lab Testing, and “TRL-4” Demo
 - Mk2 Prototype Development, Field Testing and “TRL-5” Demo
 - Arctic Field Testing and M/ADD Collaboration
 - Mobile Rover-deployed Drilling and Remote Command/Control
- **Developed/Demonstrated Novel Approach for Planetary Drilling:**
 - Dry, rotary, coring, wireline, bailing Bottom Hole Assembly
 - Low Mass: 8.5 kg BHA
 - Low Power: 100 watts-electric operation
 - Depth: Multiple meters, extensible to 10's+ meters
 - Aseptic core samples: 2.5 cm dia by 15 cm, continuous record
 - Modest Force-on-Bit: 387 N (87 lbf)
 - Rotary Speeds: 100-120 rpm
 - Modest Rate-of-Penetration: 20 cm/hr rate of penetration
 - 2 m depths demo'd in Sandstone, Ice, Unconsolidated Sand
 - Five different Drill Bit technologies explored; Multiple Auger families
 - Applicable to Mars or Moon, and Robotic or Human Missions

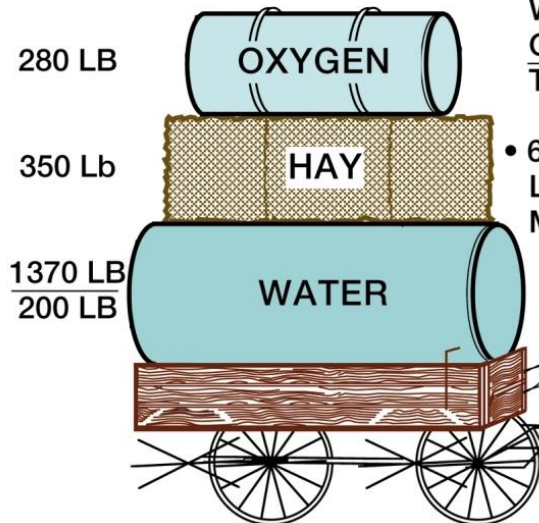


Settling the West



We wouldn't have gotten far if we couldn't use the local resources

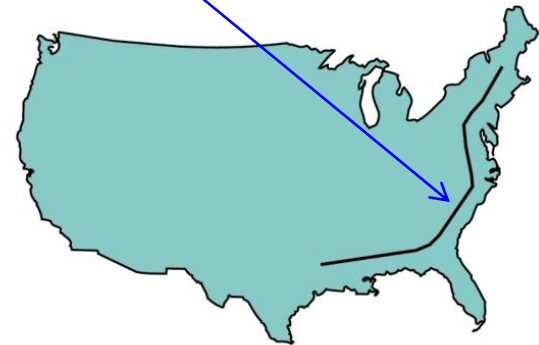
HAYBURNER ANALOGY



- MULE CONSUMABLES

HAY	15 LB/MULEDAY
WATER	58 LB/MULEDAY
OXYGEN	12 LB/MULEDAY
TOTAL	85 LB/MULEDAY

- 6 MULES CAN PULL LIGHT WAGON WITH 2000 LB MAXIMUM LOAD 25 MILES/DAY



CD-93-63713

- $$\frac{(2000 \text{ LB}) \times (25 \text{ MILES/DAY})}{(6 \text{ MULES}) \times (85 \text{ LB/MULEDAY})} = \text{RANGE}$$

- MAXIMUM RANGE = 100 MILES



Space Resources



Four major resources on the Moon:

- **Regolith:** oxides and metals
 - Ilmenite 15%
 - Pyroxene 50%
 - Olivine 15%
 - Anorthite 20%
- Solar wind volatiles in regolith
 - Hydrogen 50 – 150 ppm
 - Helium 3 – 50 ppm
 - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
 - 1-10% (LCROSS)
 - Thick ice (SAR)
- Discarded materials: Lander and crew trash and residuals

Water is the Key Resources

- Life Support
- Rocket Propellant
- Radiation Shielding

~85% of Meteorites are Chondrites

Ordinary Chondrites

FeO:Si = 0.1 to 0.5
Fe:Si = 0.5 to 0.8

87%

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Troilite - FeS

Source metals
(Carbonyl)

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal
Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles

Enstatite Chondrites 5%

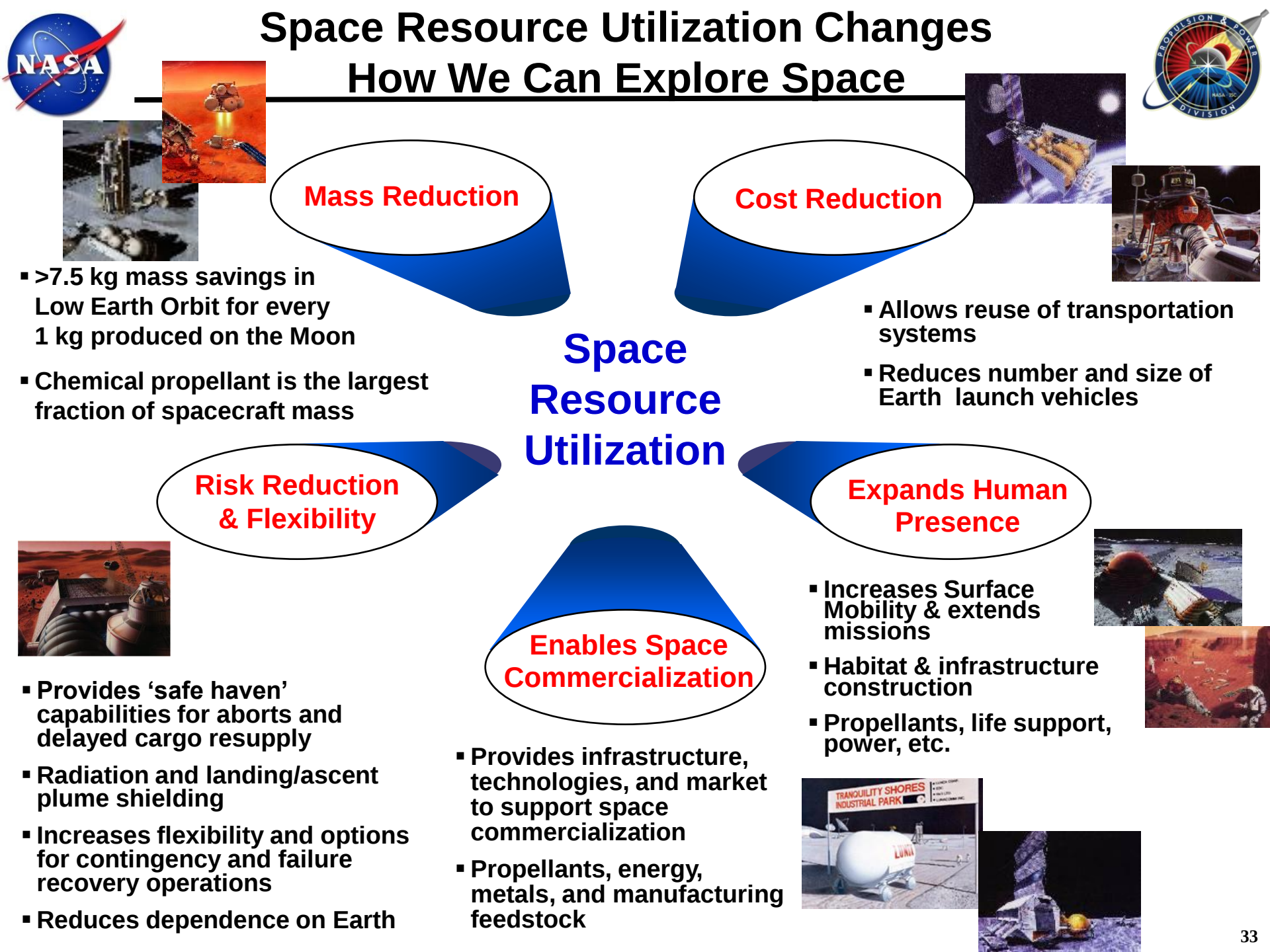
Highly reduced; silicates contain almost no FeO
60 to 80% silicates; Enstatite & Na-rich plagioclase
20 to 25% Fe-Ni
Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)



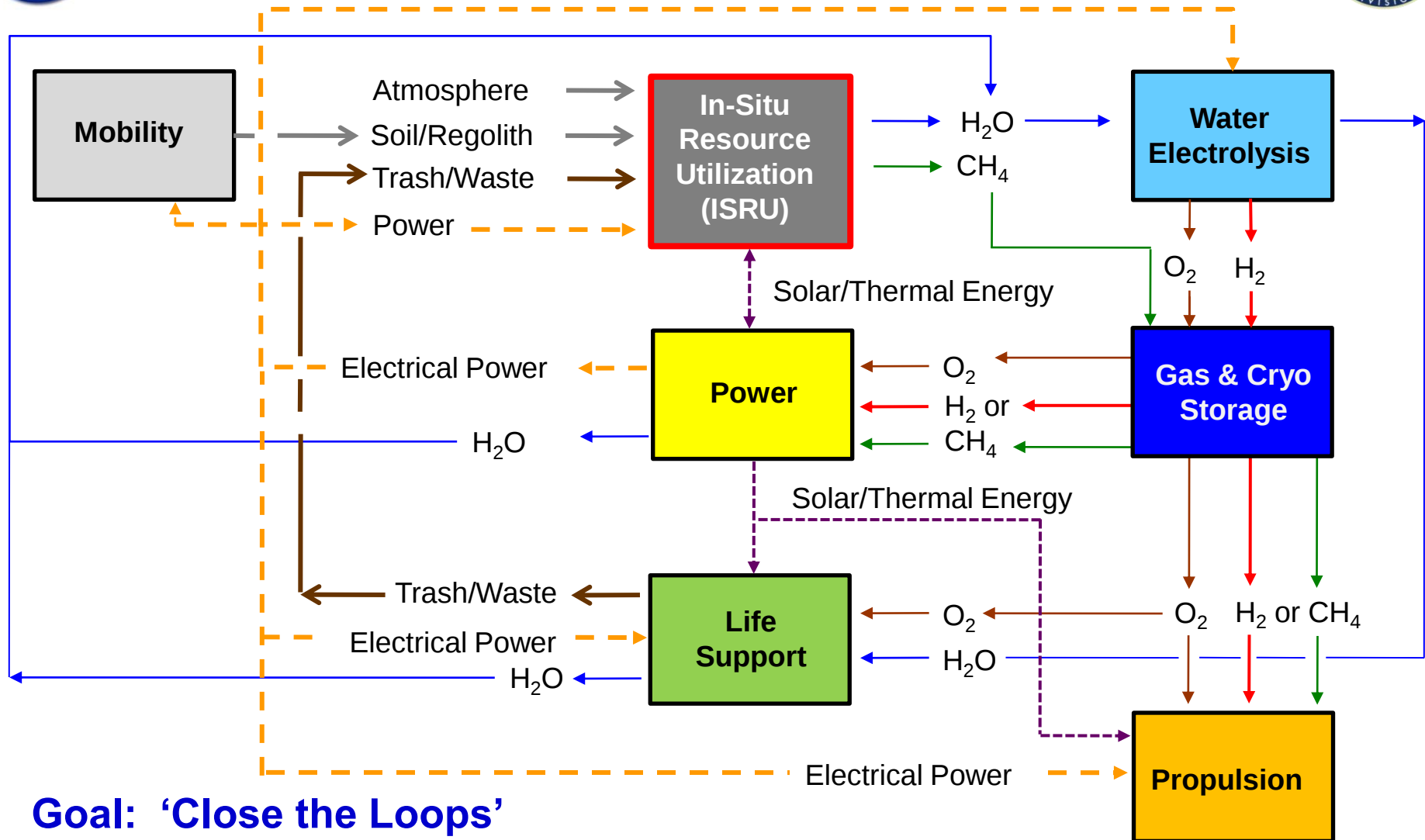
Three major resources on Mars:

- **Atmosphere:**
 - 95.5% Carbon dioxide,
 - 2.7% Nitrogen,
 - 1.6% Argon
- **Water in soil:** concentration dependant on location
 - 2% to dirty ice at poles
- Oxides and metals in the soil





Integrated Power & Consumable Cycles for ISRU – Power – Propulsion – Life Support



Goal: 'Close the Loops'

- Common fluids, pressures, quality, and standards
- Common storage, distribution, and interfaces
- Common technologies and hardware for flexibility and reduced DDT&E



NASA ISRU Development Areas



Excavation for O₂ Extraction



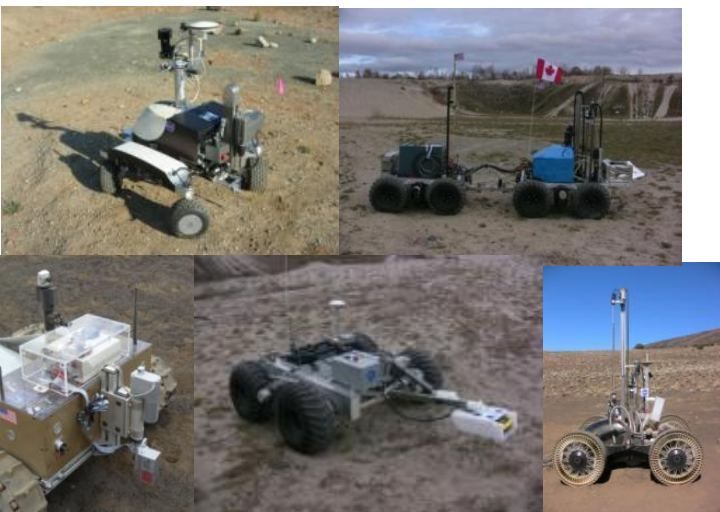
Site Preparation-Area Clearing



O₂ Production/Volatile Extraction from Soils



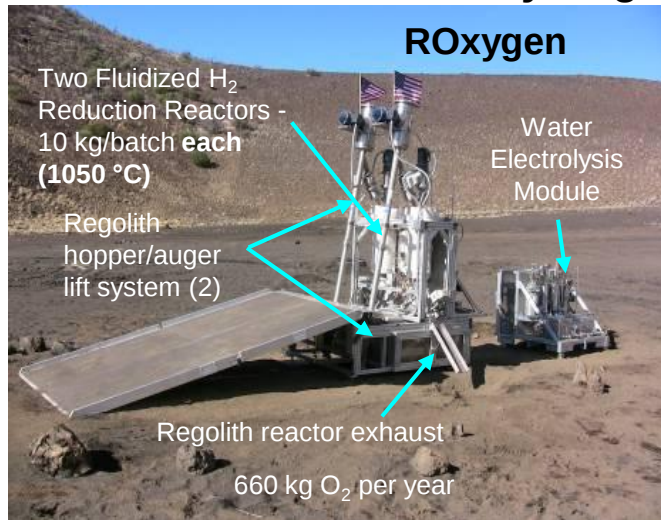
Resource Prospecting/Mapping



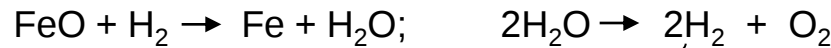
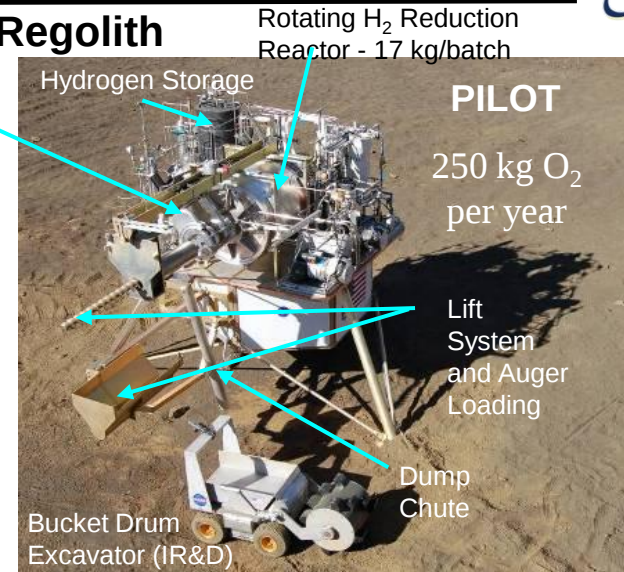
Surface Sintering/Hardening



Hydrogen Reduction of Regolith

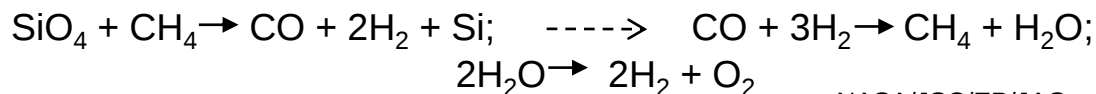
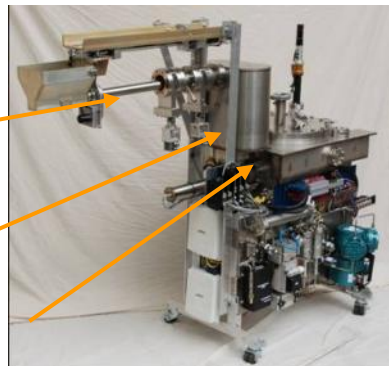


1. Heat Regolith to >900 C
2. React with Hydrogen to Make Water
3. Crack Water to Make O₂



Carbothermal Reduction of Regolith

1. Melt Regolith to >1600 C
2. React with Methane to CO
3. Convert CO to Methane & Water
4. Crack Water to Make O₂



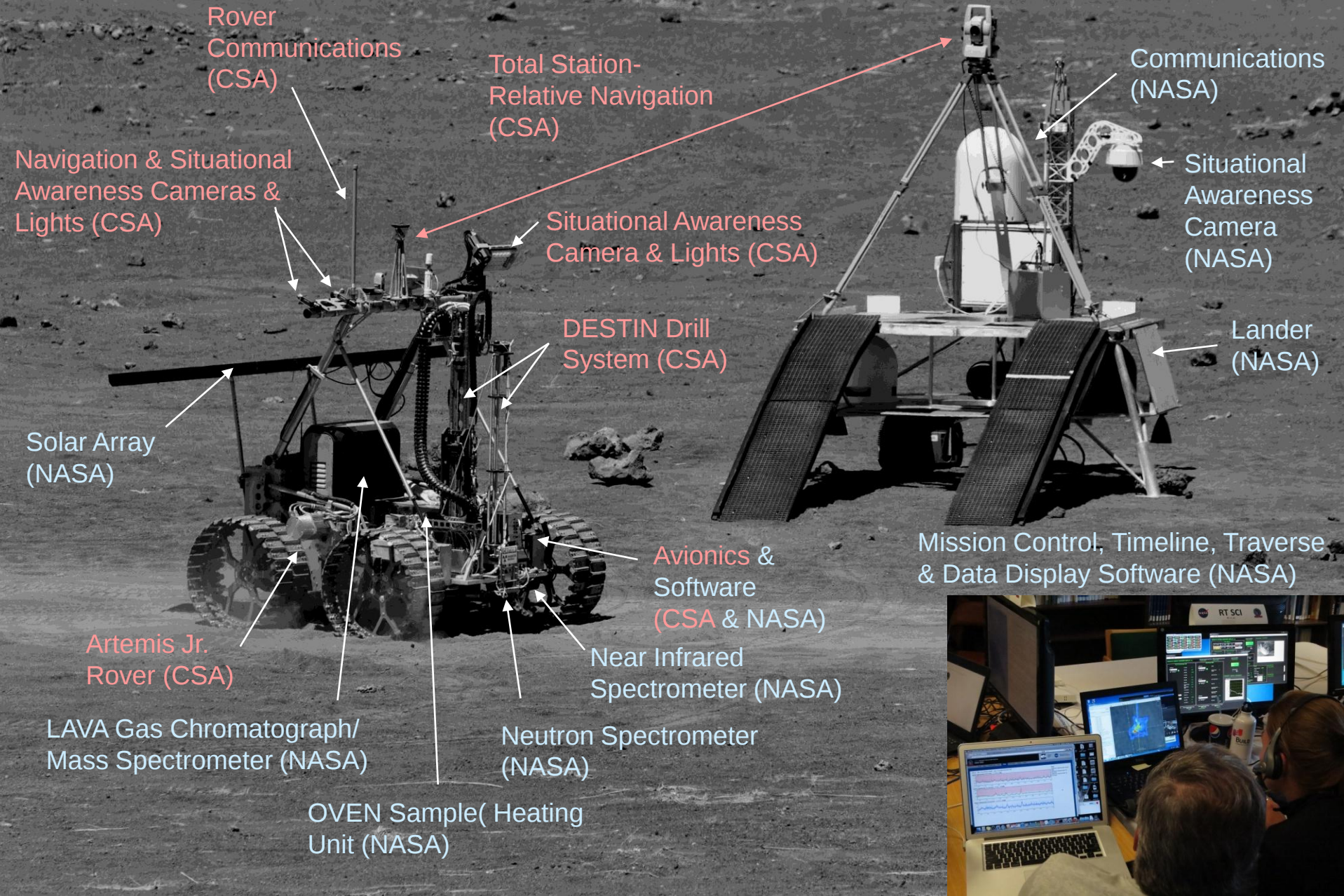
NASA/JSC/EP/JAG

Molten Electrolysis of Regolith

1. Melt Regolith to >1600 C
2. Apply Voltage to Electrodes To Release Oxygen

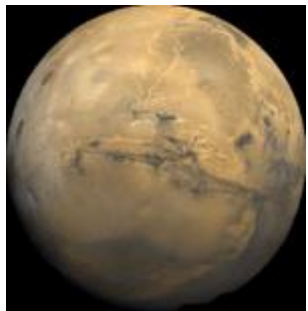


Proposed “RESOLVE” Lunar Polar Ice/Volatile Prospecting Mission





Mars Resources, Processes & Products



MARS RESOURCES

ATMOSPHERE

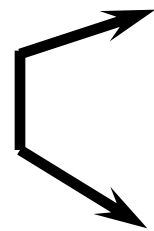
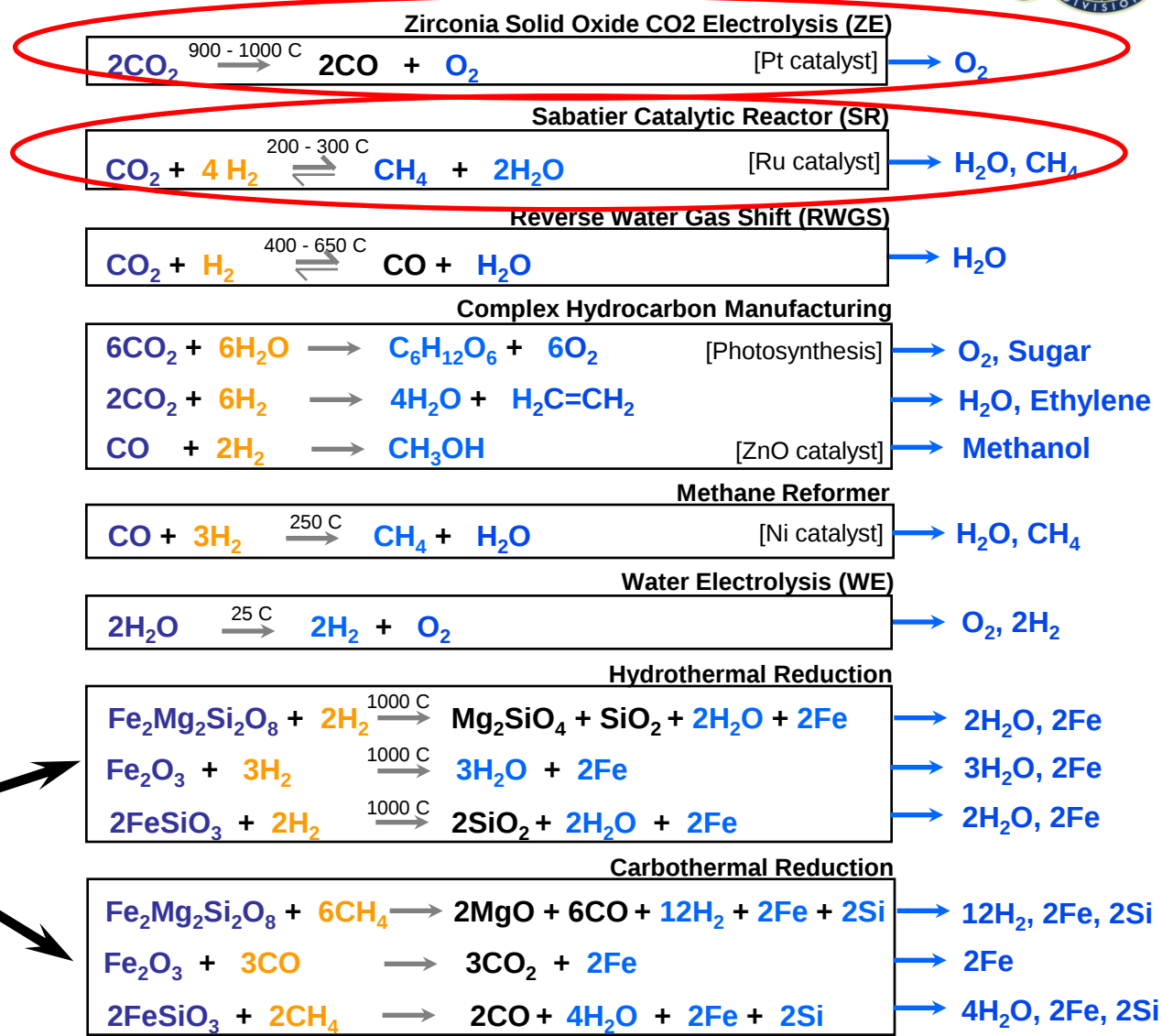
Carbon Dioxide (CO ₂)	95.5%
Nitrogen (N ₂)	2.7 %
Argon (Ar)	1.6%
Oxygen (O ₂)	0.15%
Water (H ₂ O)	<0.03%

SOIL

Fe₂Mg₂Si₂O₈
Fe₂O₃
FeSiO₃

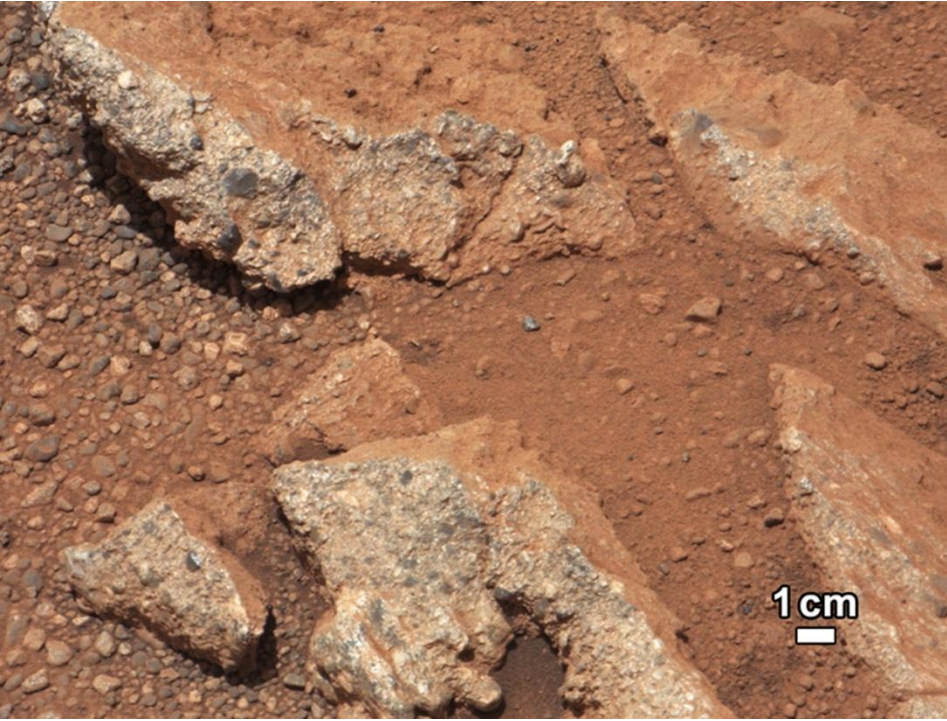
SURFACE VOLATILES

Polar Water (H ₂ O)	TBD
Perma Frost (H ₂ O)	TBD
Frozen CO ₂	TBD



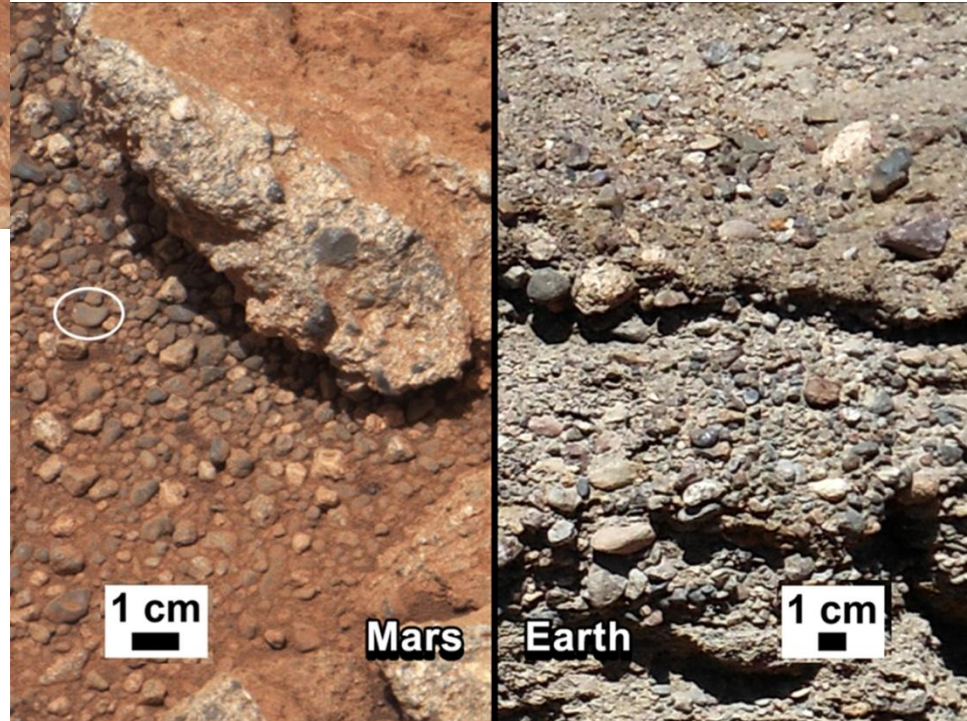
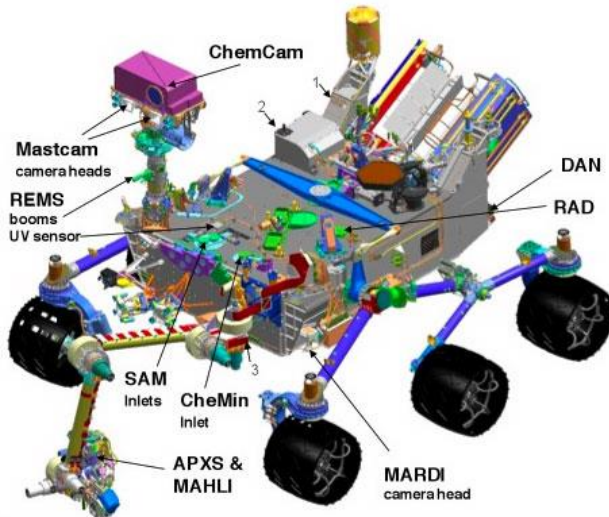
Thermal Volatile Extraction

SUB-SURFACE VOLATILES



Sedimentary Conglomerate?

- Fractured outcrop w/ clean exposed surface
- Rounded gravel clasts few cm's in size
- White matrix material
- Gravel sized rocks have eroded off



Summary

Planetary Drilling is a key technology for future space exploration

- Science: geology, climate history, astrobiology
- Resource prospecting
- Unique requirements drive unique design solutions

Planetary Resources enable robust human space exploration

- In-situ production of oxygen, water, propellants, shielding, etc.
- “7.5-to-1” gear ratio for the Moon
- Moon:
 - Regolith → Oxygen
 - Polar shadowed craters → Water ice
- Mars:
 - Carbon dioxide atmosphere → Oxygen
 - Poles → Water ice
 - Aquifers?

